

APPLICATION FOR UNITED STATES PATENT

in the name of

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for

**CURRENT TRANSFORMER BASED HIGH VOLTAGE
MEASUREMENT METHOD**

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CURRENT TRANSFORMER BASED HIGH VOLTAGE MEASUREMENT METHOD

TECHNICAL FIELD

This invention relates to voltage and current sensing.

BACKGROUND

Capacitively-coupled voltage measurement is frequently used to measure the voltage present on a high voltage conductor in high voltage alternating current electric systems. Typically, a high voltage capacitor is connected between the high voltage conductor and the secondary winding, and a load capacitor is connected between the secondary winding and the toroidal ferro-magnetic core. The high voltage capacitor and the load capacitor form a simple capacitive voltage divider from which the voltage of the high voltage conductor may be determined. Voltage measurement is often supplemented with a measurement of current flowing through the high voltage conductor. Typically, a current transformer is used to provide this current measurement by surrounding the high voltage conductor with a ferro-magnetic transformer core around which an insulated secondary winding is wound uniformly.

Although capacitively-coupled voltage sensing is widely used, the cost and precision of the capacitively-coupled sensors are closely related to the quality of the high voltage capacitors used to perform the measurements. High precision is often achieved by using closely matched foil capacitors immersed in a dielectric liquid or ceramic capacitors built with high-performance, temperature-compensating materials. These high precision capacitors generally are quite expensive.

A low cost approach is achieved by constructing a voltage-sensing capacitor as an integral part of the high voltage apparatus. The capacitance of such a capacitor is determined by the internal device geometry and the dielectric constant of an associated insulating material. The low cost approach often produces a relatively low capacitance value that limits the overall measurement accuracy of the design. Low capacitance, and therefore low energy, also presents a challenge in transmitting the measured information from the sensor to the device that is performing the voltage measurement.

Parasitic capacitance between the current transformer secondary winding and the high voltage conductor may elevate the potential of the secondary winding, which may lead to failure of the secondary winding insulation. A similar problem applies to the ferro-magnetic based transformer core if the potential is left freely floating with respect to the high voltage conductor potential. To reduce or eliminate this current transformer failure mechanism, the standard approach has been to ground the current transformer core or to add a grounded shielding electrode that protects the current transformer secondary winding.

SUMMARY

In one general aspect, simultaneous measurements of voltage and current present on a primary high voltage conductor are achieved through use of a current transformer. Capacitive coupling between the high voltage conductor and the current transformer secondary winding is used to transmit primary voltage information without affecting the current normally flowing through the current transformer secondary winding. The voltage and current information is separated, the voltage information is used to provide a voltage measurement output representative of the voltage present on the primary conductor, and the current information is used to provide a current measurement output representative of the current flowing on the high voltage conductor. The same approach may be used for each phase in a multi-phase system. Thus, capacitively coupled voltage measurement may be combined with current measurement in a single device. The approach exploits the parasitic capacitance normally present between the high voltage conductor and the current transformer secondary winding, and the parasitic capacitance normally present between the current transformer secondary winding and the ferro-magnetic core to form a simplified capacitive voltage divider from which the voltage of the high voltage conductor may be determined.

Implementations may include one or more of the following features. For example, the current measurement may be obtained through an electronic circuit or a secondary transformer, and the voltage measurement may be obtained through an electronic circuit. A neutral current measurement may also be obtained, for example, through an electronic circuit or a transformer.

A capacitive voltage divider may be used in providing the voltage measurement. In multi-phase systems, each phase would have a corresponding capacitive voltage divider. The capacitive voltage divider may have first and second capacitances, where the first capacitance

is between the high voltage conductor and the secondary winding of the current transformer and the second capacitance is between the secondary winding of the current transformer and the transformer core. The first and second capacitance may be, for example, the parasitic capacitance between the high voltage conductor and the secondary winding of the current transformer and the parasitic capacitance between the secondary winding of the current transformer and the transformer core of the current transformer connected to a reference potential. A ground potential may be used as a reference potential. In another implementation, any potential may be used as the reference potential. For example, any potential with a voltage difference with respect to the high voltage conductor being measured may be used. In one implementation, the second capacitance may be increased by adding an external capacitor between the current transformer secondary winding and the reference potential. In another implementation, the second capacitance may be increased by adjusting the parasitic capacitance. The parasitic capacitance may be adjusted, for example, by adjusting the device geometry. In one implementation, the second capacitance has a value from approximately 0.001 to 10 microfarads and forms a high pass filter network in combination with a drain resistor that is connected between the current transformer secondary winding and ground, where the cutoff frequency of the high pass filter network may be set between approximately 1 to 0.001 hertz.

An electronic circuit may be used in providing the voltage measurement. For example, the electronic circuit may have an operational amplifier, a resistor connected to the operational amplifier and a terminal of the current transformer, and a drain resistor connected to the operational amplifier.

In another implementation, an auxiliary transformer may be used to provide the current measurement. Alternatively, an electronic circuit may be used to provide the current measurement. The electronic circuit may include an operational amplifier connected to the current transformer and a burden resistor connected to the operational amplifier.

In a further implementation, the neutral current of a multi-phase system may be measured. For example, a transformer with a separate winding for each phase may be used to provide the neutral current measurement. Alternatively, the neutral current may be measured using an electronic circuit.

Another implementation includes canceling from the voltage measurement crosstalk induced by one or more additional phases in a multi-phase system. For example, voltage measurements may be obtained for the additional phases, a product may be generated for each additional phase by multiplying the additional phase voltages by a corresponding
5 predetermined constant, and the product for each additional phase may be subtracted from the voltage measurement. In one example, there are three phases in the multi-phase system.

The crosstalk may be cancelled by an electronic circuit. The electronic circuit may include an operational amplifier, a connecting resistor connected between the input and output of the operational amplifier, and a resistor associated with an additional phase connected to the
10 operational amplifier. In another implementation, the crosstalk may be cancelled by computer software.

The current transformer secondary winding may be protected from insulation failure induced by a transient voltage. For example, a surge suppressor may be connected between the transformer secondary winding and ground.

Although primarily intended for medium voltage power systems, simultaneous
15 measurement techniques may be applied to other voltage levels and system frequencies. Moreover, by reducing the number of components required, the techniques offer a very low cost solution for combined current and voltage measurement. Components for implementing the approach may be retrofitted to existing systems to add voltage sensing capability to older
20 transformer installations. The techniques may be used in a multi-phase system, such as a three-phase system, or in a single phase system.

Other features and advantages will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

25 FIG. 1 is a front view of a three-phase auto-recloser system using a voltage sensor with active crosstalk cancellation.

FIG. 2 is a partially cut-away side view showing the internal construction of a single module, including a voltage sensor, of the three-phase auto-recloser system shown in FIG. 1.

FIG. 3 is a cross-sectional side view of a combined current and voltage sensor.

FIG. 4 is a cross-sectional side view illustrating parasitic capacitance in the sensor of FIG. 3.

FIG. 5 is a block diagram of a current and voltage sensor for single-phase voltage.

FIG. 6 is a block diagram of a current and voltage sensor for three-phase voltage.

5 FIG. 7 is a block diagram of a voltage sensor and crosstalk cancellation system used by the system of FIG. 1.

FIG. 8 is a schematic diagram of an electronic circuit for performing crosstalk cancellation used by the cancellation system of FIG. 7.

Like reference symbols in the various drawings indicate like elements.

10 DETAILED DESCRIPTION

FIG. 1 shows a three-phase auto-recloser 100 that is connected by a signal transmission cable 105 to an electronic control 110. High voltage conductors (not shown) are connected to terminals 115, 120, 125, 130, 135, and 140, extending from modules 145 of the auto-recloser 100.

15 Referring to FIG. 2, each module 145 includes a capacitively-coupled voltage sensor 200 integrated around a side arm conductor 205 associated with a respective one of terminals 115, 120, and 125. The voltage sensing electrode 200 is axially symmetric about the high voltage conductor 205 and placed within the diameter of a current transformer 210. A current transformer corona shield 215 surrounds the current transformer and provides additional dielectric shielding for the voltage sensing electrode 200 to reduce external field effects. The combination of the capacitively-coupled voltage sensor and the current transformer is used to produce the voltage and current measurements.

20 As illustrated in FIG. 3, the combined current and voltage sensor 200 can be positioned within a solid insulating body 300 or immersed into an insulating gas or liquid. The sensor 200 includes a toroidal ferro-magnetic core 305 and an insulated secondary winding 310 that is wound uniformly around the core 305. The current carrying high voltage conductor 315 is centered and passes through the central core opening. FIG. 3 shows the combined current and voltage sensor 200 for a single phase. In a multi-phase power system network, a sensor 200 is needed for each individual phase.

FIG. 4 shows the parasitic capacitance present in the combined current and voltage sensor system. Specifically, FIG. 4 shows the parasitic capacitance 400 present between the secondary winding 405 and the high voltage conductor 410. In addition, FIG. 4 shows the parasitic capacitance 415 present between the secondary winding 405 and the transformer core 420. The transformer core is typically connected to a reference potential, which may be electrical ground or another potential. Once transformer core 420 is grounded or placed at the reference potential, parasitic capacitances 400 and 415 form a simple capacitive divider. In this configuration, the secondary winding voltage will float at the output potential determined by the following equation:

$$V_{out} = V_m \times \frac{C_1}{C_1 + C_2}.$$

In the equation, C_1 is the parasitic capacitance 400 between the high voltage conductor and the secondary winding and C_2 is the parasitic capacitance 415 between the secondary winding and the transformer core.

The value of capacitor 400 is determined by the design of the current transformer. The output potential V_{out} can be adjusted by increasing the value of the capacitance 415 so as to adjust the voltage divider ratio. The value of the capacitance 415 may be increased, for example, by adding an external capacitor between the current transformer secondary winding and the reference potential and/or by adjusting the value of the parasitic capacitance present between the secondary winding and the transformer core. The measured voltage and current signals are combined on a single pair of conductors (i.e., the current transformer secondary wires) and must be separated for actual measurement and display.

FIG. 5 shows a circuit that separates the voltage and current signals using a differential amplifier in combination with a burden resistor. The output voltage level can be adjusted by varying the value of capacitance 415 (shown in FIG. 4) in current transformer 505. The value of the capacitance 415 may be increased, for example, by adding an external capacitor between the current transformer secondary winding and the reference potential and/or by adjusting the value of the parasitic capacitance present between the secondary winding and the transformer core. For example, the value of capacitors 540 and/or 550 may be varied. Under normal operating conditions, the output voltage V_{out} typically is set between 0.5 and 10 V_{RMS} . Surge protection components may be introduced into the circuit to limit the maximum voltage that

can be developed during power system transients, lightning strikes, and other over-voltage events. The surge suppressor protective level is normally coordinated at approximately 110% to 500% of the typical steady state operating level. Different surge suppressor technologies such as MOV, TVS, Sidactor, and Sparc-Gap may be used.

5 High voltage conductor 501 carries a current I and a voltage V , and is coupled to current transformer 505. Current transformer 505 is connected to a voltage measuring circuit 510 and a current measuring circuit 515.

The voltage measuring circuit 510 includes a capacitor 540 and a surge protection component 545 that are connected in parallel between a terminal 516 of current transformer 505 and ground. A resistor 520 is connected between a terminal 516 of current transformer 505
10 and an input 533 to an operational amplifier 535. The other input 534 to operational amplifier 535 is connected to ground. A capacitor 550 and a surge protection component 555 are connected in parallel between a terminal 517 of current transformer 505 and ground. A resistor 525 is connected between the terminal 517 of current transformer 505 and the input 533 to operational amplifier 535. A drain resistor 530 is connected between the input terminals 533
15 and 534 of operational amplifier 535. The output 536 of operational amplifier 535 is proportional to the voltage of high voltage conductor 501.

The current measuring circuit 515 includes a burden resistor 560 connected between terminal 516 and terminal 517 of current transformer 505. The burden resistor 560 is further
20 connected between input terminals 563 and 564 of an operational amplifier 565. The output 566 of operational amplifier 565 is proportional to the current in high voltage conductor 501. In other implementations, the described operational amplifier and burden resistor combination are replaced with an auxiliary transformer.

FIG. 6 shows a circuit 600 to extract the zero sequence (neutral) current 690
25 information in the case of a multi-phase power system network. This neutral current information is often necessary in a multi-phase power system network. The neutral current is extracted by summing together the three individual phase currents 670, 675, 680. The circuit also provides outputs for the individual phase voltages 636_A, 636_B, and 636_C, and outputs for the individual phase currents 666_A, 666_B, and 666_C.

30 High voltage conductors 601_A, 601_B, and 601_C carry currents I_A , I_B , and I_C and voltages V_A , V_B , and V_C , and are coupled to current transformers 605_A, 605_B, and 605_C respectively.

Each of current transformers 605_A, 605_B and 605_C is connected to a corresponding one of voltage measuring circuits 610_A, 610_B, and 610_C, and to a corresponding one of current measuring circuits 615_A, 615_B, and 615_C. Current transformers 605_A, 605_B, and 605_C are further connected to neutral current measuring circuit 695.

5 For ease of description, components of the voltage measuring circuits 610_A, 610_B, and 610_C and the current measuring circuits 615_A, 615_B, and 615_C are referred to collectively rather than individually. Thus, for example, capacitors 640_A, 640_B, and 640_C are referred to as capacitor 640.

10 Each voltage measuring circuit 610 includes a capacitor 640 and a surge protection component 645 that are connected in parallel between a terminal 616 of current transformer 605 and ground. A resistor 620 is connected between a terminal 616 of current transformer 605 and an input 633 to an operational amplifier 635. The other input 634 to operational amplifier 635 is connected to ground. A capacitor 650 and a surge protection component 655 are connected in parallel between a terminal 617 of current transformer 605 and ground. A resistor 625 is connected between a terminal 617 of current transformer 605 and an input 633 to operational amplifier 635. A drain resistor 630 is connected between the input terminals 633 and 634 of operational amplifier 635. The output 636 of operational amplifier 635 is proportional to the voltage of the corresponding high voltage conductor 601.

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20 Each of the current measuring circuits 615 includes an auxiliary transformer 665 connected between terminal 616 and terminal 617 of current transformer 605. The output 666 of auxiliary transformer 665 is proportional to the current in the corresponding high voltage conductor 601. In other implementations, an operational amplifier and burden resistor combination may be substituted for the described auxiliary transformer 665.

25 The neutral current measuring circuit 695 includes windings 670_A, 670_B, and 670_C of an auxiliary transformer 680. These windings are connected between auxiliary transformer 665_A, 665_B, and 665_C and current transformer 605_A, 605_B, and 605_C. The neutral current output 690 sensed by transformer 680 is proportional to the sum of the three phase currents I_A , I_B , and I_C .

30 Referring to FIG. 7, each of phases V_A , V_B , and V_C of the three-phase AC voltage is measured by an associated one of the high-voltage capacitive sensors 701_A, 701_B, and 701_C. The outputs of the three high voltage capacitor sensors 701_A, 701_B, and 701_C are combined by a signal processing circuit 700 located within a housing of the auto-recloser 100 (FIG. 1). The

signal processing circuit 700 includes load capacitors 705_A, 705_B, and 705_C, which are used to form simple capacitive voltage dividers in combination with the high voltage capacitors 701_A, 701_B, and 701_C. The output of each of the voltage dividers is connected to a corresponding one of surge protection networks 710_A, 710_B, and 710_C and drain resistors 715_A, 715_B, and 715_C.

5 The drain resistors are used to eliminate any static charge which may be present on the outputs of the voltage dividers.

The signals then are passed to high impedance buffer circuits 720_A, 720_B, and 720_C, which are used to minimize the voltage sensor phase error. From the buffer circuits, the signals pass through programmable gain stages 725_A, 725_B, and 725_C to account for manufacturing
10 tolerances of the high voltage capacitors 701_A, 701_B, and 701_C. The programmable gain stages correct the individual sensor ratio so that the divider ratios are the same for each phase of the three-phase AC voltage. The required gain calibration parameters for the programmable gain stages can be programmed by using a calibration port 730 and are stored in non-volatile memory 735.

15 The calibrated individual sensor outputs are fed through temperature compensation circuits 740_A, 740_B, and 740_C, which use ambient temperature measurements to compensate for the temperature variations of the individual capacitive voltage dividers. The value required for temperature compensation is determined by the type of dielectric used in capacitors 701 and 705, and is constant in any given sensor design.

20 Next, the individual sensor outputs are fed through crosstalk compensation circuits 745_A, 745_B, and 745_C to provide first order crosstalk cancellation. Alternatively, higher orders of crosstalk cancellation may be provided. The crosstalk cancellation may be performed by signal processing hardware, and may be implemented, for example, as an application-specific integrated circuit (ASIC). Alternatively, the crosstalk cancellation may be performed by a
25 computer program running on either a general purpose computer or a special purpose computer. Crosstalk cancellation minimizes the effect of crosstalk between the three voltage sensors. The crosstalk is caused by the simple high voltage capacitor construction and the relative proximity of the three-phase voltage conductors.

In the presence of crosstalk, the measured voltage present on the output of the
30 individual voltage sensors can be described by the following equation (1):

$$\begin{aligned}
V_A^{measured} &= V_A + k_1 V_B + k_2 V_C \\
V_B^{measured} &= V_B + k_3 V_A + k_4 V_C \\
V_C^{measured} &= V_C + k_5 V_A + k_6 V_B
\end{aligned} \tag{1}$$

The system of equations in (1) is a system of three equations with three unknowns, namely V_A , V_B , and V_C . These unknowns, V_A , V_B , and V_C , are the voltages to be measured. The system of equations above describes a linear superposition caused by the proximity of the three sensors to each other and the imperfect shielding of the individual sensors from crosstalk. The three sensors for phases A, B, and C are used to measure three voltages, $V_A^{measured}$, $V_B^{measured}$, and $V_C^{measured}$. The measured voltage of each phase contains crosstalk terms from the other two phases. For example, the measured voltage $V_A^{measured}$ contains the term $k_1 V_B$ from phase B and the term $k_2 V_C$ from phase C. In equation (1), the coupling constants k_1 , k_2 , k_3 , k_4 , k_5 , and k_6 are determined by the auto-recloser device geometry. The coupling constants can be measured and will remain constant as long as the device geometry is kept constant. For the symmetric three-phase design shown in FIG. 1, the coupling constants are symmetric ($k_1=k_3=k_4=k_6$ and $k_2=k_5$). The full solution of the system of equations in (1) is shown below in equation (2).

$$\begin{aligned}
V_A &= \frac{V_A^{MEAS} - k_4 k_6 V_A^{MEAS} - k_1 V_B^{MEAS} + k_2 k_6 V_B^{MEAS} - k_2 V_C^{MEAS} + k_1 k_4 V_C^{MEAS}}{1 - k_1 k_3 - k_2 k_5 - k_4 k_6 + k_1 k_4 k_5 + k_2 k_3 k_6} \\
V_B &= \frac{-k_3 V_A^{MEAS} + k_4 k_5 V_A^{MEAS} + V_B^{MEAS} - k_2 k_5 V_B^{MEAS} - k_4 V_C^{MEAS} + k_2 k_3 V_C^{MEAS}}{1 - k_1 k_3 - k_2 k_5 - k_4 k_6 + k_1 k_4 k_5 + k_2 k_3 k_6} \\
V_C &= \frac{-k_5 V_A^{MEAS} + k_3 k_6 V_A^{MEAS} - k_6 V_B^{MEAS} + k_1 k_5 V_B^{MEAS} + V_C^{MEAS} - k_1 k_3 V_C^{MEAS}}{1 - k_1 k_3 - k_2 k_5 - k_4 k_6 + k_1 k_4 k_5 + k_2 k_3 k_6}
\end{aligned} \tag{2}$$

Equation (2) can be simplified when the crosstalk levels (as indicated by coefficients k_1 , k_2 , k_3 , k_4 , k_5 , and k_6) are sufficiently low. For example, when the crosstalk levels are equal to or less than approximately 0.1 (10%), the set of equations in (2) may be simplified so that the corrected output values are described by the following equation (3):

$$\begin{aligned}
V_A^{corrected} &= V_A^{measured} - k_1 V_B^{measured} - k_2 V_C^{measured} \\
V_B^{corrected} &= V_B^{measured} - k_3 V_A^{measured} - k_4 V_C^{measured} \\
V_C^{corrected} &= V_C^{measured} - k_5 V_A^{measured} - k_6 V_B^{measured}
\end{aligned} \tag{3}$$

Equation (3) is derived from equation (2) as follows. First, consider the denominator of equation (2). The denominator can be approximated as the value of 1 when the crosstalk levels

are sufficiently low, for example 0.1 or less. The second term in the denominator of equation (2) is equal to or less than 0.01 if the coefficients k_1 and k_3 are equal to or less than 0.1 because $k_1 k_3 \leq 0.1 * 0.1 = 0.01$. The same analysis applies to the third term, $k_2 k_5$, and the fourth term, $k_4 k_6$. Therefore, the second, third, and fourth term each contribute 1% error or less. The fifth and sixth terms are even smaller. The fifth term is equal to or less than 0.001 if the coefficients k_1 , k_4 , and k_5 are equal to or less than 0.1 because $k_1 k_4 k_5 \leq 0.1 * 0.1 * 0.1 = 0.001$. The same analysis applies to the sixth term, $k_2 k_3 k_6$. Therefore, the fifth and sixth terms each contribute 0.1% error or less. When k_1 , k_2 , k_3 , k_4 , k_5 , and k_6 are equal to or less than 0.1, the denominator becomes $1 - 0.01 - 0.01 - 0.01 + 0.001 + 0.001 = 0.972$, which is almost equal to 1.00. Thus, for crosstalk terms approximately equal to or less than 0.1, the denominator effectively reduces to 1.

The numerator can be simplified in a similar fashion. When the crosstalk levels are sufficiently low, for example 0.1 or less, the second, fourth, and sixth terms in the numerator are small contributors which can be eliminated. For example, in the second term of the first equation in (2), the factor $k_4 k_6 \leq 0.1 * 0.1 = 0.01$. Eliminating the small contributors in the numerator of equation (2) results in the simplified first order crosstalk cancellation of equation (3).

Equation (3), as simplified from equation (2), only satisfies the first order crosstalk cancellation because the measured terms already contain errors introduced by adjacent sensors in the other phases. However, it is appropriate to use equation (3) in certain cases, such as an analog circuit implementation with crosstalk levels (as indicated by coefficients k_1 , k_2 , k_3 , k_4 , k_5 , and k_6) approximately equal to or less than 0.1 (10%).

Because the values in equation (3) contain second order errors due to the simplification from equation (2), the resulting voltages at the left hand side of equation (2) are not called V_A , V_B , and V_C . Instead, the terms $V_A^{\text{corrected}}$, $V_B^{\text{corrected}}$, and $V_C^{\text{corrected}}$ are used to capture this difference between equations (2) and (3).

As previously mentioned, the crosstalk cancellation described above may be performed by signal processing hardware, and may be implemented, for example, as an application-specific integrated circuit (ASIC). Alternatively, the crosstalk cancellation may be performed by a computer program running on either a general purpose computer or a special purpose computer.

After crosstalk cancellation is performed, the sensor output for each of phases V_A , V_B , and V_C of the three-phase AC voltage is fed to a corresponding one of differential output drivers 750_A, 750_B, and 750_C. The output drivers 750 amplify the measurement signals for each phase V_A , V_B , and V_C of the three-phase AC voltage and make them ready for transmission through a cable. Differential outputs are used to enhance the immunity of the transmitted signal to externally induced noise. Finally, the sensor outputs are fed to surge protection networks 755_A, 755_B, and 755_C for transmission on the cable 105.

Referring to FIG. 8, a circuit 800 for economically performing the crosstalk cancellation function is shown for a single phase, in this case phase "A," of the three-phase system. The inputs V_A , V_B , and V_C shown in FIG. 8 may be obtained, for example, from outputs 636_A, 636_B, and 636_C of FIG. 6. The inputs V_A , V_B , and V_C shown in FIG. 8 are proportional to the voltages of high voltage conductors as shown, for example, by 601_A, 601_B, and 601_C of FIG. 6.

Input V_A is connected to the positive input 810 of an operational amplifier 805. A resistor 825 is connected between input V_B and the negative input 815 of operational amplifier 805. A resistor 830 is connected between input V_C and the negative input 815 of operational amplifier 805. Resistor 835 is connected between the negative input 815 and the output 820 of operational amplifier 805. The output 820 of operational amplifier 805 represents the first order crosstalk cancellation of the errors introduced by phases B and C into the measurement of phase A, as shown in equation (2) above. The same approach just described for one phase applies equally to the other two phases.

It will be understood that various modifications may be made. For example, the crosstalk compensating function can be performed in software on a programmable numeric device. Such an implementation is also an attractive way to apply the full solution to a simple system of linear equations shown in equation (3), so as to eliminate higher order errors introduced by equation (2).

As another example, in FIG. 5 the differential amplifier/burden resistor combination may be substituted with an auxiliary current transform. Also, in FIG. 5, a single capacitor and/or resistor with center tapped auxiliary current transformer. It is also possible to eliminate resistor R.

Accordingly, other implementations are within the scope of the following claims.